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Electromagnetic Pulse (EMP) Coupling Codes for Use With the Vulnerability/Lethality (V/L) Taxonomy

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Based on the vulnerability/lethality (V/L) taxonomy developed by the Ballistic Vulnerability Lethality Division (BVLD) of the Survivability Lethality Analysis Directorate (SLAD), U.S. Army Research Laboratory (ARL), a nuclear electromagnetic pulse (EMP) coupling V/L analysis taxonomy has been developed. A nuclear EMP threat to a military system can be divided into two levels: 1) coupling to a system level through a cable, antenna, or aperture; and 2) the component level. This report will focus on the initial condition, which includes threat definition and target description, as well as the mapping process from the initial condition to damaged components state. EMP coupling analysis at a system level is used to accomplish this. This report introduces the nature of EMP threat, interaction between the threat and target, and how the output of EMP coupling analysis at a system level becomes the input to the component level analysis. Many different tools (EMP coupling codes) will be discussed for the mapping process, which corresponds to the physics of phenomenology. This EMP coupling V/L taxonomy and the models identified in this report will provide the tools necessary to conduct basic V/L analysis of EMP coupling.

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1. INTRODUCTION

A nuclear detonation generates an intense electromagnetic pulse (EMP) field that is a potential hazard to military systems. The EMP field can propagate directly through building walls, or can couple to various energy collectors, such as cables (power or data), antennas, and apertures, which carry the transient signals inside of buildings or shielding enclosures. Since the undesired signal (transient current and voltage) can cause permanent damage or operational impairment to military systems, an EMP coupling analysis is a very critical program. The EMP coupling analysis is designed to evaluate system response, to analyze the shielding effectiveness of different structures, and to utilize transient protection devices. To conduct the EMP coupling analysis in an integrated manner within the Survivability Lethality Analysis Directorate (SLAD), the following EMP vulnerability/lethality (V/L) taxonomy has been developed based on the current V/L analysis process structure.

2. V/L SPACES AND MAPPINGS

Since this EMP coupling V/L taxonomy is based on the Ballistic Vulnerability Lethality Division (BVLD) V/L taxonomy, Figure 1 is reproduced here from the U.S. Army Research Laboratory (ARL) report titled, "Current Directions in the Vulnerability/Lethality Process Structure" (Walbert, Roach, and Burdeshaw 1993).

3. THE NUCLEAR EMP V/L TAXONOMY

Based on the above structure, a specific nuclear EMP V/L taxonomy has been generated as shown in Figure 2. At the present time, the nuclear EMP V/L taxonomy is developed up to Level 2. Future efforts should be concentrated on developing a mathematical fault tree to represent the $O_{2,3}$ mapping and further down to the battlefield utility level. Level 1 describes the initial conditions which include the threat definition and target description. Using the $O_{1,2}$ mapping, physics of phenomenology (numerical electromagnetic analysis computer codes and databases), the state of Level 2 (damaged components) is defined as follows: analog/digital circuit upset and analog/digital circuit burnout. This report will concentrate on the initial conditions and the numerical electromagnetic analysis computer codes for $O_{1,2}$ mappings. Another report (Ruth 1994), focuses on the rest of the $O_{1,2}$ mapping process, mainly electrical overstress on components and the resulting paths into Level 2.

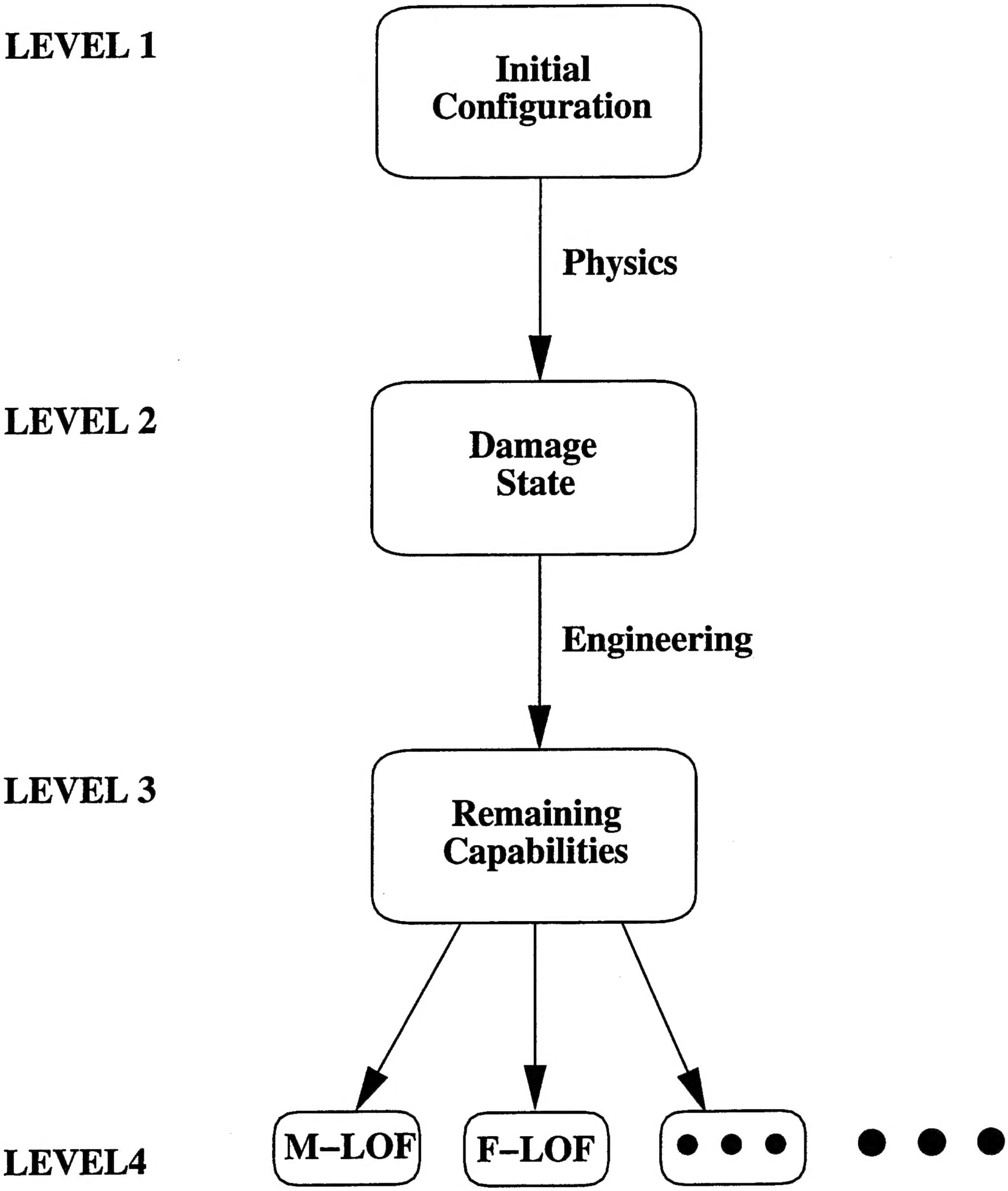

Figure 1. The vulnerability analysis process.

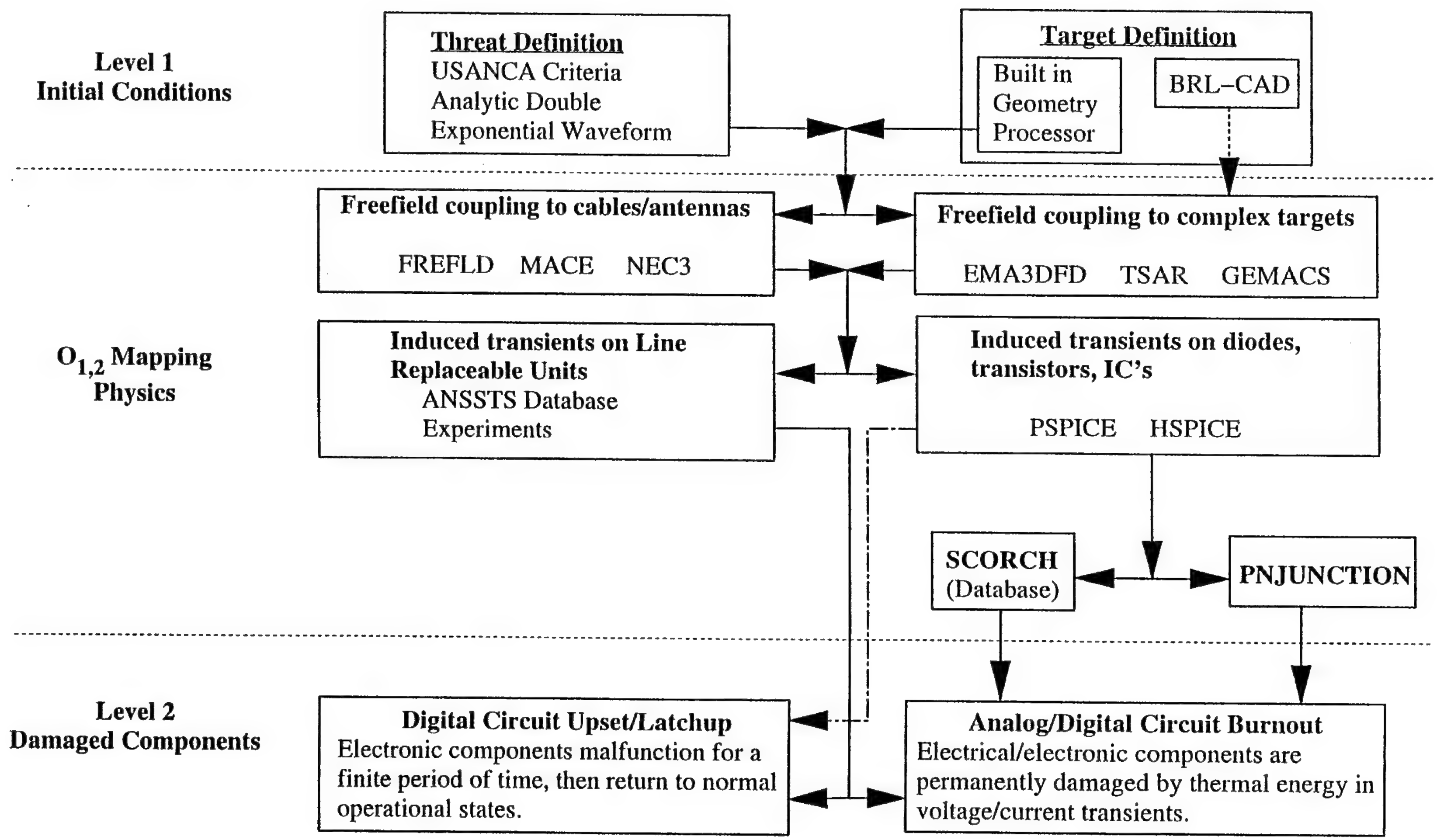

Figure 2. Nuclear EMP V/L taxonomy.

3.1 Level 1: Initial Conditions (Threat Definition and Target Description). The threat definition can be established by the U.S. Army Nuclear and Chemical Agency (USANCA) criteria for Army systems. However, a generalized double exponential waveform from "EMP Engineering and Design Principles" by Bell Laboratory (1984) describes the behavior of EMP threat including fast rise time, high amplitude, and long fall time.

3.1.1 Threat (EMP) Definition. A nuclear detonation produces an EMP which has a peak field strength of tens of kilovolts per meter within a few nanoseconds. There are three different kinds of EMP environments depending on the height of the nuclear burst: surface burst EMP, airburst EMP, and high altitude EMP (HEMP). The EMP coupling analysis usually concerns an HEMP event in which a nuclear burst occurs above 40 km (Bell Laboratories 1984). This environment has the largest geographical coverage through the electromagnetic field radiation. In this radiation region, EMP propagates radially outward from the burst as a plane wave, and the bulk of EMP energy lies within the radiofrequency spectrum. Since a generalized EMP waveform has the short rise time (typically 5 ns) and the long fall time to cover high- and low-frequency content, an analytical double exponential waveform can be used for theoretical analysis. The analytical double exponential EMP electric field time behavior is given by Bell Laboratories (1984),

$$E(t) = 5.25 \times 10^4 \left[\exp\left(-4 \times 10^6 t\right) - \exp\left(-4.76 \times 10^8 t\right)\right],$$

in volts per meter, where t is in seconds. The peak amplitude of this pulse is 50 kV/m, and a rise time to reach 90% of the peak amplitude is about 5 ns, and a time to fall back to 50% of the peak amplitude is about 200 ns. Figure 3 plots the time waveform of this constructed HEMP electric field. Since many EMP energy collectors (antenna, cable, and waveguide) are frequency selective, it is important to find the EMP energy distribution in the frequency domain. The Fourier transform of the generalized EMP electric field time waveform is calculated to represent the frequency content (Bell Laboratories 1984)

$$\varepsilon(\omega) = \frac{2.47 \times 10^{13}}{\left(j\omega + 4 \times 10^6\right)\left(j\omega + 4.76 \times 10^8\right)}$$

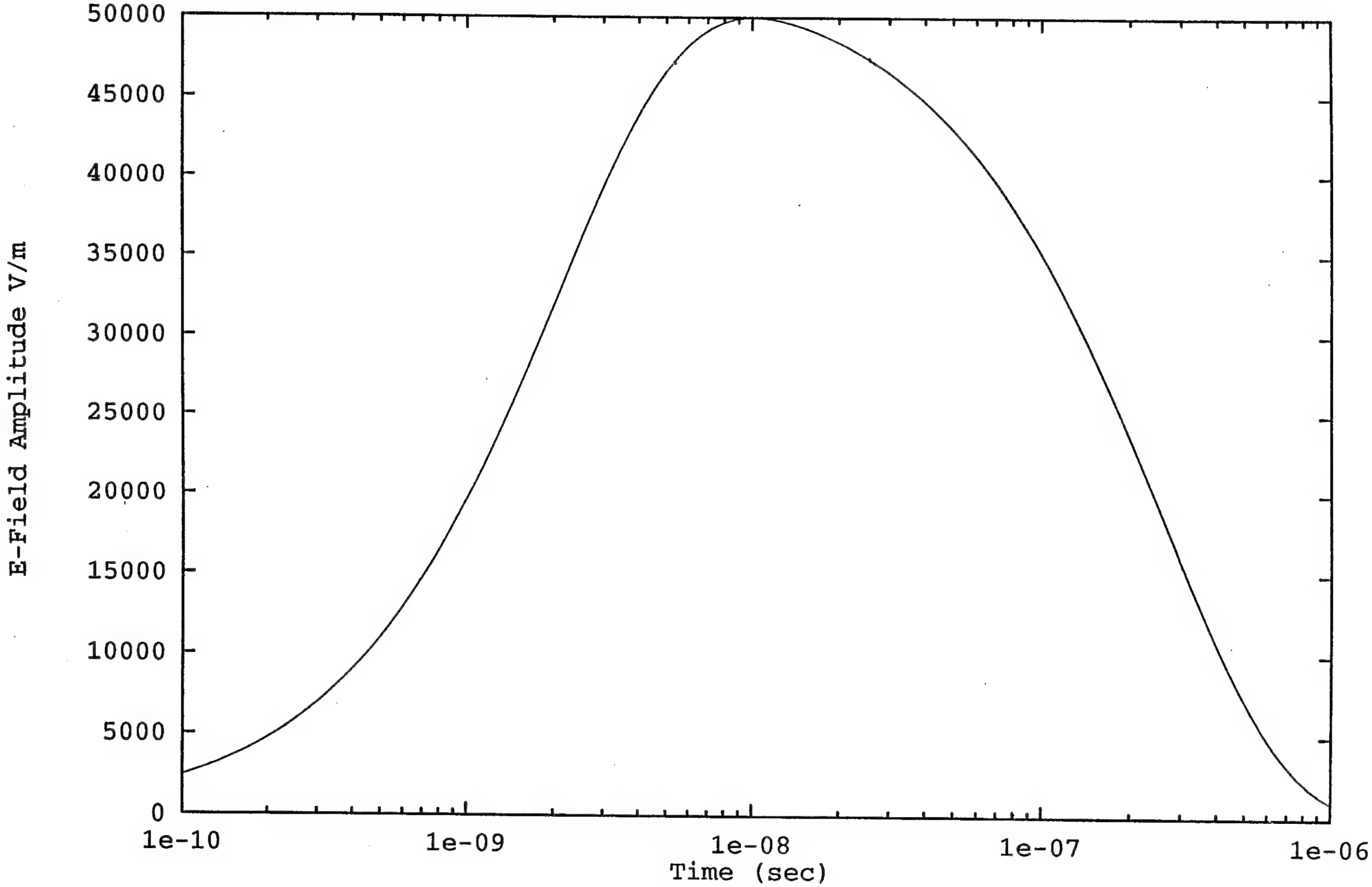

Figure 3. HEMP E-field time domain waveform.

in volts-seconds per meter, where ω is the radian frequency. Figure 4 is a Bode plot of the magnitude of the EMP frequency spectrum. As Figure 4 illustrates, the EMP frequency spectrum covers a broad frequency range unlike a manmade signal.

3.1.2 Target Description. The target description in EMP coupling analysis depends on the numerical electromagnetic analysis tool being used. Usually, each EMP coupling code provides a set of commands to describe the target configuration. The EMP coupling codes for antenna and cable problems use wires and patches to describe target configuration. The other EMP coupling codes for more complex systems use boxes, cylinders, and cylinder end caps as well as wires and patches. Since the target description process is very tedious and time consuming for complex systems such as aircraft or tanks, there are many ancillary target description utilities. There is software called "WINGAUGE" that models a target description for input to the EMP coupling code "GEMACS" which will be explained in more detail in the next section. "WINGAUGE" is a user-friendly target description utility based on the personal computer "Windows" environment. In order to process complex problems, a graphical UNIX workstation has to be employed. For the UNIX environment, the U.S. Army Research Laboratory Computer-Aided Design (BRL-CAD) is a very good target description utility. As soon as the interface programs between BRL-CAD and various EMP coupling computer codes are available, BRL-CAD will be the prime target description utility.

3.1.3 EMP Coupling. Any external conducting structures act as unintentional receiving antennas under the EMP environment threat. If the external conducting structures terminate inside the building or system, these external conducting structures provide good transmission paths for transient currents to enter the building or system and couple to critical equipment or components. There are many numerical solutions to explain the physics of a coupling mechanism related to solving Maxwell's equations.

3.2 $O_{1,2}$ Mapping. The main physics of phenomenology in $O_{1,2}$ mapping for EMP coupling analysis is solving Maxwell's equation using different kinds of numerical techniques. Figure 2 shows two groups of EMP coupling codes depend upon its capability. However, in this section, each EMP coupling computer code will be introduced individually.

3.2.1 FREFLD. Program FREFLD is a transmission line solution of the EMP coupling to a coaxial cable over a finitely conducting earth. The approach of solving the coaxial coupling problem is the

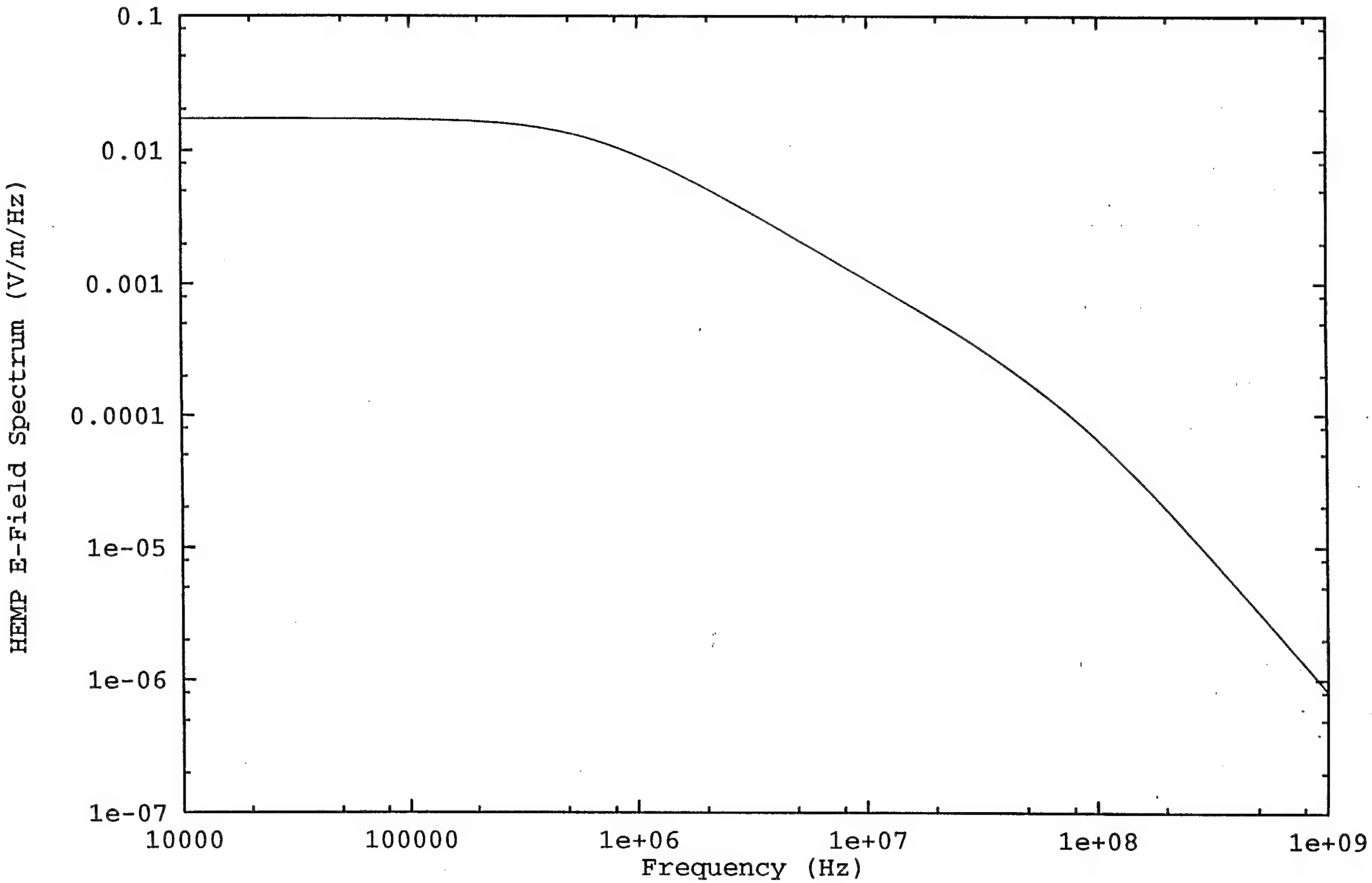

Figure 4. <u>HEMP E-field spectrum</u>.

development and general solution of the transmission line equations for a single wire over a real earth excited by an arbitrary field. Then, using the EMP waveform assumed as a plane wave input, the transmission line current and voltage will be determined as a function of position along the wire. Then the final solution, which is the voltage between the shield and center conductor at each end of the cable, or the current through the termination will be generated by combining the above result with a shield coupling model.

There are three different representations of an EMP waveform in FREFLD. The first one is a double exponential waveform given by Gray and Hill (1985),

$$E(t) = A\left(e^{-\beta t} - e^{-\alpha t}\right),$$

where A, α, and β are constants that govern the amplitude, rise time, and fall time, respectively. The second presentation is a rational exponential equation of the form (Gray and Hill 1985)

$$E(t) = \frac{Ae^{\alpha t}}{1 + e^{(\alpha + \beta)\tau}},$$

where

$$A = A_p \frac{\alpha + \beta}{\alpha}\left(\frac{\alpha}{\beta}\right)^{\frac{\beta}{\alpha+\beta}},$$

$$\tau = t - t_p + \frac{1}{\alpha+\beta}\ln\left(\frac{\alpha}{\beta}\right),$$

A_p = peak amplitude,

t_p = time to peak amplitude,

and α and β are constants as before. This is a more realistic representation of the high frequency (above 100 MHz) behavior of an HEMP.

The third analytical representation of EMP waveform is a multiexponential sum. It represents the output waveforms of most EMP simulators as well as an idealized EMP waveform. The exponentials are each multiplied by a time function that gives a zero first derivative at zero time, which is an important feature when numerical inverse transforms are used. The multiexponential representation in the time domain is given by

$$E(t) = (A_1 - A_2)(1 + \eta t)e^{-\eta t} + (A_3 + A_4)(1 + \beta t)e^{-\beta t} - A_1(1 + \alpha t)e^{-\alpha t} - A_3(1 + \gamma t)e^{-\gamma t}$$
$$+ A_4 U(t - t') \{[1 + \beta'(t - t')]e^{-\beta'(t - t')}\} - [1 + \alpha'(t - t')]e^{-\alpha'(t - t')},$$

where $U(t - t')$ is a unit step function and the other terms are all constants (Gray and Hill 1985).

FREFLD also has a built-in target description, which is mainly cable layout configuration including cable length, radius of center conductor, shield thickness, and termination of both ends. Since a cable is the most common energy collector for military systems, FREFLD is a valuable EMP coupling analysis tool to handle many cable problems with approximation on termination. The output of FREFLD, external (shield) or internal (conductor) current, can be input to the next part of the $O_{1,2}$ mapping, which is component-level analysis.

3.2.2 Microcomputer-Assisted EMP Coupling Estimator (MACE). MACE has the capability of analyzing cables, antennas, and cylinder shape of targets, such as missiles or aircraft. MACE estimates external current and charge densities on cylinders with different lengths and radii. It also calculates the induced transient voltage and current on semi-infinite aerial lines by HEMP as a function of angle of incidence and soil conductivity. One of the important features of MACE is estimating the equivalent current and voltage source due to coupling through an aperture to an internal cable. Even though MACE has more capabilities for EMP coupling analysis and is a very user-friendly program, the output is an order of magnitude approximation with very limited threat and target description.

MACE uses "an exponential over an exponential" as the basic EMP transient waveform (Jaycor 1985).

$$E(t) = \frac{kE_p \exp[\alpha(t - t_0)]}{1 + \exp[(\alpha + \beta)(t - t_0)]}$$

where

$$k = \frac{\alpha + \beta}{\alpha}\left(\frac{\alpha}{\beta}\right)^{\frac{\beta}{\alpha + \beta}} \text{ is the normalization constant}$$

α = exponential rise rate constant

β = the exponential decay rate constant

E_p = peak electric field

t_0 = time shift constant.

MACE is a very useful EMP coupling code for first cut approximation in a short time period since it requires a minimum amount of understanding in electromagnetic field theory to use the code. Since MACE provides only limited shapes and configurations, the target description process is a matter of changing dimensions from the given objects. MACE generates current, voltage, or electric field on the test object so that the output can be used for the next part of the $O_{1,2}$ mapping process.

3.2.3 Numerical Electromagnetics Code 3 (NEC3). NEC3 computes a solution of Maxwell's integral equations using the method of moments (MOM) technique. Whereas the above two coupling codes are using a simplified transmission line theory equation, NEC3 solves actual Maxwell's equations using MOM technique. Wires are modeled in NEC3 by solving the thin-wire form of the electric field integral equation, and surface patches are modeled with the magnetic field integral equation (MFIE). The EMP threat environment is defined by plane wave generalized double exponential EMP waveform characteristics or actual experiment data from EMP freefield simulator. The target description is done using two basic geometry shapes such as thin wires and surface patches. The external skin currents and voltages can be found on the target and fed into the next part of the $O_{1,2}$ mapping process.

3.2.4 Three-Dimensional Finite Difference (3DFD) Code. The approximate solution of Maxwell's equation using the centered FD technique for EMP coupling analysis on complex shapes is used by 3DFD. The centered FD technique means that the derivative of a function at an interested point is obtained by using two values of the function on the left and right side of that particular point. If f(x) is a continuous function of a single variable x, the function can be expanded in a Taylor series at a particular point x_0 as follows (Rudolph 1990):

$$f\left(x_0 + \frac{\Delta x}{2}\right) = f(x_0) + \frac{1}{2}\Delta x\, f'(x_0) + \frac{1}{8}\Delta x^2\, f''(x_0) + \frac{1}{48}\Delta x^3\, f'''(x_0) + \ldots.$$

$$f\left(x_0 - \frac{\Delta x}{2}\right) = f(x_0) - \frac{1}{2}\Delta x\, f'(x_0) + \frac{1}{8}\Delta x^2\, f''(x_0) - \frac{1}{48}\Delta x^3\, f'''(x_0) + \ldots.$$

Subtracting these equations gives,

$$f\left(x_0 + \frac{\Delta x}{2}\right) - f\left(x_0 - \frac{\Delta x}{2}\right) = \Delta x\, f'(x_0) + \frac{1}{24}\Delta x^3 f'''(x_0) + \ldots.$$

This may now be solved for $f'(x_0)$ to give,

$$f'(x_0) = \frac{1}{\Delta x}\left[f\left(x_0 + \frac{\Delta x}{2}\right) - f\left(x_0 - \frac{\Delta x}{2}\right)\right] - \frac{1}{24}\Delta x^2\, f'''(x_0) - \ldots.$$

This equation proves the earlier statement of the centered FD technique. This equation also shows that as Δx gets smaller, the more accurate solution will be obtained.

Using this technique, the following differential form of Maxwell's equation is solved to study EMP coupling to the complex target which is made of many cells (Rudolph 1990).

$$\nabla \times H = J + \varepsilon \frac{\partial E}{\partial t}$$

$$\nabla \times E = -\mu \frac{\partial H}{\partial t}$$

$$\nabla \cdot E = \frac{\rho}{\varepsilon}$$

$$\nabla \cdot H = 0$$

The last two divergence equations describe initial conditions. By taking divergence of both sides of the first two equations, the curl equations become differential form as follows:

$$\nabla \cdot (\nabla \times H) = \nabla \cdot J + \varepsilon \frac{\partial}{\partial t} (\nabla \cdot E)$$

$$\nabla \cdot (\nabla \times E) = -\mu \frac{\partial}{\partial t} (\nabla \cdot H) \ .$$

Since the divergence of the curl is zero, the previous equations become:

$$\varepsilon \frac{\partial}{\partial t} (\nabla \cdot E) + \nabla \cdot J = 0 \ .$$

$$\frac{\partial}{\partial t} (\nabla \cdot H) = 0 \ .$$

Conservation of charge can be shown as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot J = 0 \ .$$

Therefore the original equation becomes a differential form of equations as follows:

$$\frac{\partial}{\partial t} (\nabla \cdot E) - \frac{\rho}{\varepsilon} = 0$$

$$\frac{\partial}{\partial t} (\nabla \cdot H) = 0 \ .$$

Depending upon the size of the target, interest of frequency range, and computing resources, the cell size has to be determined. As the cell size gets smaller, the resolution of target description and the output get better; however, it requires longer computing time and resources. The generic EMP waveform is

available for threat definition along with experiment data, and the target is described by combining many cubical cells. The output can be found in the form of surface current and charges on the surface, which can readily be changed to a form of input to the next mapping process.

3.2.5 Temporal Scattering and Response (TSAR) 2.3. TSAR (pronounced like "czar") is a large-scale electromagnetic modeling package with the capability of reading BRL-CAD target description files. TSAR solves Maxwell's equations in the time domain on a rectangular Cartesian grid using the FD time domain method. TSAR is not only a computational engine for solving scattering and coupling problems, but also a user-friendly program because of its capability to interface with graphical pre- and postprocessing programs such as BRL-CAD, ANASTASIA, IMAGE, and SURFACE. It requires a properly formatted data file that includes the target description (made of cubical cells) as well as an input file with the user specifications. A unique feature of TSAR is a capability of understanding BRL-CAD file as an input file. Since BRL-CAD will be a common preprocessing program for future analysis of the Chemical-Biological and Nuclear Effects Division (CBNED), TSAR is a valuable tool for EMP coupling analysis in the division. TSAR can use an arbitrary plane wave, electric, and magnetic dipole as an incident field and compute responding fields and currents in the near or far fields.

- Inputs (McLeod 1992). There are six different kinds of inputs to TSAR: compile time parameters, far field projection parameters, run time input file, grid file, user defined pulse files, and incident field functions. The last two inputs are optional. Compile time parameters and far field projection parameters are FORTRAN "PARAMETER" statements that define the size of the problem arrays. The run time input file controls general flow of the TSAR operation such as specifying how the problem is to be run and what output is to be generated. The grid file contains the model of the target to be analyzed. In the user-defined pulse file, the user defines a specific incident field to replace the internal pulse shapes. At last, the user provides the incident field functions, which are FORTRAN functions to run TSAR in a scattered field mode.

- Output (McLeod 1992). There are many different kinds of output files that can be generated. First, data can be recorded at any point in the target within any time frame and sampled at any fixed time interval. These spatial points do not have to be on the particular FD grid because TSAR can interpolate to any position and direction within the grid. It also has the capability to project results outside the grid to the near or far field zones. TSAR generates outputs in the form of electric field, magnetic field, and conduction current density. These output quantities can be plotted by a program called "SURFACE."

In addition to the output data, there is a verification file that contains all the inputs to the code and the status of progress for debugging and verification purpose. Also, a file can be generated to store the incident pulse shape to verify its shape or use in deriving a transfer function.

• ANASTASIA: A solid model based 3DFD mesh generator (Laguna 1990). FD analysis codes require regularly spaced sample points as an input which can be called a grid or mesh. ANASTASIA is a software package that allows 3DFD meshes to be generated automatically from a geometric description of the problem known as a solid model such as BRL-CAD model. There are three steps to take to generate appropriate meshes from a solid model. The first step is the creation of the solid model. The second step is to use a mesh generator to create a mesh from the solid model. The third step is to use a graphic program to verify the correctness of the generated mesh. The solid model must be created with MGED, the solid modeler in the BRL-CAD package. Then ANASTASIA generates 3D meshes from the solid model generated by MGED. The final step is to verify the correctness of the mesh using IMAGE software.

• IMAGE (McLeod and Allison 1990). IMAGE was developed at the Lawrence Livermore National Laboratory for the purpose of mesh verification for FD time domain grids. IMAGE is a valuable tool to find bugs and design flaws in the mesh generation process. It is a fully interactive tool for use on high-speed graphics workstations such as the SiliconGraphics workstation. It also has a capability of displaying only parts of the mesh at once so that the large meshes could be checked. IMAGE version 3.3 is a well-tested, graphical interactive tool for the verification and visualization of large FD time domain meshes.

3.2.6 General Electromagnetic Model for the Analysis of Complex Systems (GEMACS) (Coffey, Kadlec, and Coffey 1990). GEMACS is designed for general purpose electromagnetic analysis of complex systems using various techniques with a user-oriented environment. It contains MOM formalism for thin wire and surface patch model with or without geometrical theory of diffraction (GTD) interactions to solve exterior problems. It also provides an FD formalism in the frequency domain to solve interior problems. One of the powerful techniques of GEMACS is the mathematics necessary to connect exterior and interior solutions when apertures are present. GEMACS is implemented in six sequentially executable FORTRAN programs (called "modules"). The GEMACS code uses a high-level language (FORTRAN and C) so that the user has control over the computational sequence. Debug and trace options with error messages help the user identify sources of fatal errors. GEMACS provides spherical wave, plane wave, and dipole wave as an incident waveform and set of geometry commands to describe complex targets. There is a program

called "GAUGE" as a pre- and postprocessing (target description and plotting routine) utility to develop a model for GEMACS. In the near future, an interface utility between BRL-CAD and GEMACS will be developed so that GEMACS can work with an existing BRL-CAD target description library. GEMACS can compute current on the object and the field's distribution, either inside or outside of the object.

• MOM Formulations (Coffey, Kadlec, and Coffey 1990). One MOM formalism includes the thin wire Pocklington integral equation, pulse plus sine plus cosine expansion functions, point matching, and a charge redistribution scheme at multiple wire junctions. The thin wire Pocklington integral equation can be used to solve actual wires, wire grid models for conducting surface patches, or a combination of these. The user specifies the interested frequency range, loading on the cable, the presence of ground plane with ground conductivity, and the excitation. The wires can be excited by plane or spherical waves at any segments not necessarily at either end, and the antennas can be excited by voltage sources. The wires can be loaded with fixed (as a function of frequency) lumped loads, series or parallel of resistor, inductor, and/or capacitor networks.

A second MOM formalism is the use of the MFIE to model a surface patch. This technique assumes two orthogonal current directions for each surface patch. A connection between wire and patch has to be made at the patch centers. In the region of a wire connection to a patch, four subpatches are generated, and the continuity of current equation at the center of the patch takes into account the singular component due to the current flowing from the wire into the surface. Therefore, the MFIE can be employed for modeling a conducting surface instead of wire grid modeling approach. Using these two MOM formalisms, almost any metal structure can be modeled in a certain degree of resolution.

• GTD Formulation (Coffey, Kadlec, and Coffey 1990). Using the GTD technique, an electrically large object can be modeled in bulk instead of a combination of many wire segments and patches. Fields scattered by the electrically large object are determined by optic principles such as ray tracing and reflection coefficients. The present GTD capability in GEMACS uses a minimum phase iterative ray tracing algorithm. The code is designed to handle an arbitrary large number of GTD modeling elements and an arbitrarily large number of rays bouncing off those elements. To use GTD techniques, the test object has to be modeled by a set of canonical objects such as planar plates, cylinders, and the cylinders' end caps. Using the incident field and the frequency information, the scattered fields are obtained directly from the sources and geometry by tracing all geometrical optics paths from the sources to the field points and reflecting and diffracting the waves which follow these paths from the surfaces, edges, and corners

of the geometry elements. GTD techniques are a very useful tool to compute scattered fields for the electrically large objects when the detailed structure elements are not important. The GTD formalism requires that the test object geometry has to be fully specified without using symmetry property.

- FD Formalism (Coffey, Kadlec, and Coffey 1990). Both MOM and GTD techniques may be used to solve exterior electromagnetic radiation and coupling problems. A frequency domain FD technique is an approximation solution to the differential form of Maxwell's equations to solve an interior problem, such as calculating the field's distribution of any shape of enclosures. Rather than using the standard sparse matrix FD approach, GEMACS version 5 instead uses a unique cell-by-cell connection process that minimizes computer storage requirements. This allows inclusion of thin-wire scatterer, arbitrary boundary conductivity, user-specified dielectrics, and arbitrary field points. Based on the boundary information of the cavity provided by the user, GEMACS generates FD cells within the cavity volume. The size of cellular grid defaults to a maximum value which is 0.1 wavelengths in each of the three rectilinear directions, but can be set to other values as long as the value stays in numerically stable region. In order to find currents induced on thin wires and electric fields at arbitrary points within the cavity, the FD method has to be employed. The following restrictions apply for implementing FD formalism: (1) no penetration of the cavity into another interior or exterior region; (2) thin wires within the cavity must have length-to-diameter ratios on the order of 5:1 or larger; (3) the wire radius must be 5–10 times smaller than the FD cell dimension; and (4) junctions of wires are permitted within the cavity, but junctions should not be made at angles less than about 20°.

4. CONCLUSION

Based on a vulnerability lethality analysis taxonomy as applied to nuclear EMP coupling, a number of models have been identified which should provide a good foundation for analysis within SLAD. Based on the preliminary study on the identified EMP coupling computer codes, NEC3 could be the primary analysis tool for simple structures attached with antennas and cables and GEMACS could be the prime candidate for more complex systems such as tank, ship, or aircraft. These codes are essential tools to follow through the EMP coupling analysis process of the nuclear EMP V/L taxonomy. Another important process of the nuclear EMP V/L taxonomy is component assessment down to semiconductor level. The component level analysis under EMP environment requires input from the EMP coupling analysis on the system level. Therefore, the coupling analysis and the component assessment process are directly related in chronological order to complete the physics mapping process of the nuclear EMP V/L taxonomy.

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